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Biomass resources and their bioenergy potential estimation: A review

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ABSTRACT

Biomass and bioenergy potential estimation has been worldwide research highlights in renewable energy field to get comprehensive understand of bioenergy development, especially under the situation of energy crisis. This paper reviews the results of previous studies that investigated biomass resources and their bioenergy potential estimation. It is organized from the perspectives of traditional vs. newly-introduced approaches and present vs. future. First, according to the methods used in relative studies, existing studies were divided into two categories: statistical data based and RS-GIS based. Second, concerning about the future of bioenergy, biomass and bioenergy potential estimation under different scenarios in the future were also reviewed and summarized according to the dominant factor considered in simulation. At last, based on the reviews above, questions and the future of bioenergy potential estimation were proposed so as to provide some instructions for bioenergy development.

Contents

1. Introduction

With the development of human society and the population growth, the surging demand for food and energy is forcing human beings and earth's terrestrial ecosystems confronting with unprecedented pressures. Since industrial revolution, the demand and consumption of energy have increased significantly. Energy shortage and security have become key issue all around the world. On

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Table 1
Biomass resources categories according to their origination.

Categories			Representative materials
Productive biomass	Terrestrial	Carbohydrate	Sugar cane, corn, sweet sorghum
		Starch	Maize, cassava, sweet potato
		Cellulose	Tropical grasses, poplar, sycamore
		Hydrocarbon	Eucalyptus, green coral
		Grease	Oil palm, rapeseed, sunflower
	Aquatic	Freshwater	Water hyacinth[a]
		Ocean	Large kelp[a]
		Microorganism	Green algae, photosynthetic bacteria[a]
Unused biomass	Residues from Agriculture Forestry Fisheries	Agriculture	Wheat bran, straw
			Vegetable residues, processing residues
		Animal Husbandry	Animal manure[b]
			Farm residues[b]
		Forestry	Secondary forest
			Woodland remnants
			Crippled material in plants
		Fisheries	Jettisoned and dead fish[b]
	Waste	Municipal Waste	Municipal and pulp sludge[b]
		Garbage	Family garbage, feces[b]

Note: The table is re-generated according to reference [4].

[a] Indicate the amount of these types of biomass can hardly be estimated.

[b] Indicating that the amount of these types could only be collected through statistical data. Besides statistical data, RS and GIS methods could be integrated into the estimation method of rest ones.

the other hand, greenhouse gases generated from fossil fuels are continuously accumulating in the atmosphere, which are the major pollutants of air pollution and important factors for global climate change. Facing the dual pressures mentioned above, more environmental friendly and more economical alternative renewable energy sources are gradually coming into view. Global climate change, food security and energy security are pressing us to seek a more sustainable way when developing our production, life and national economy. Bioenergy is one indispensible form of renewable energy among many from other sources (wind, solar, hydraulic, geothermal etc.) [1]. The use of biomass and bioenergy can significantly reduce greenhouse gas emissions. The carbon dioxide it gives off when it is burned is counterbalanced by the amount absorbed when the plant in question was grown. Thus, bioenergy production based on biomass resources is an essential substitute for fossil energy and has attracted general attention around the world. It currently contributes about 9–13% of the total global energy supply [2].

Biomass, as a renewable energy source, is biological material from living, or recently living organisms, most often referring to plants or plant-derived materials[1] . Bioenergy is renewable energy made available from materials derived from biological sources. Biomass can either be used directly, or indirectly—once or converted into another type of energy product such as biofuel. Biomass resources estimation is a thorough spatial and statistical count of all the types of biomass. While, bioenergy potential estimation, is the estimation of potential amount of energy contained in biomass resources. Since the use of bioenergy could not only supplement the shortage of fossil fuels, but also stabilize atmospheric concentrations of greenhouse gases below dangerous levels and help achieve the objectives of the framework convention on climate change (FCCC), the question about how much and how far bioenergy could help arises. Studies about bioenergy potential estimation could give a thorough understanding of the sources, types, amount and distribution of bioenergy potentials. All these aspects can help assess how much bioenergy can substitute and supplement energy shortage, the possible degree to which bioenergy could contribute to decrease greenhouse gas, and how to arrange rational development and utilization of bioenergy.

[1] Biomass Energy Center. Biomassenergycentre.org.uk. Retrieved on 2012–02–28.

Bioenergy potential estimation is the first step to understand bioenergy from the industrial chain and its development potential in the future. In order to take a thorough look at the bioenergy industry, researchers have done considerable studies about biomass and bioenergy potential, not only in global and regional scale, but also in national and local scale. In this paper, we review existing researches about biomass and bioenergy potential estimation through different aspects. The main objective of this paper is to reveal current research progress of biomass and bioenergy potential estimation, from the perspectives of methods, results, current situation and the future. Based on analysis above, the questions and the future of biomass and bioenergy potential estimation are discussed to look forward to its further development.

2. Categories of biomass resources

According to the definition of biomass by European Commission, there are various kinds of biomass resources such as products, by-products and residues from agriculture, forestry and relative industries, as well as the non-fossil, biodegradable parts of industry and municipal solid waste (MSW) [3]. Existing biomass resources categories are mostly based on their use and purpose. There are two wide-accepted ones. The first is productive biomass and unused biomass. The other divides biomass resources into agricultural, forestry and aquatic biomass, waste biomass and planted biomass [4]. Table 1 gives a detailed category of biomass resources and examples for every type, as well as the potential estimation methods.

When estimating the amount of biomass resources, the types are selected according to the accessibility of data in a certain region, thus it is hardly to find studies gathering all the resources types in their estimation. For example, in the estimation study of global bioenergy resources in 2050 done by Smeets et al., their first choice is energy plant, woods, residues and wastes including agricultural and forestry collection and processing residues, excrement and urine, MSW, etc. [5]. Li et al. considered four main types of biomass when estimating biomass potential in China's agricultural residues and wastes and forestry processing waste, firewood, excrement and urine and MSW [6]. Crop residues are the most commonly considered biomass types [7,8]. While, some food crops are adopted as main raw material for energy production in some

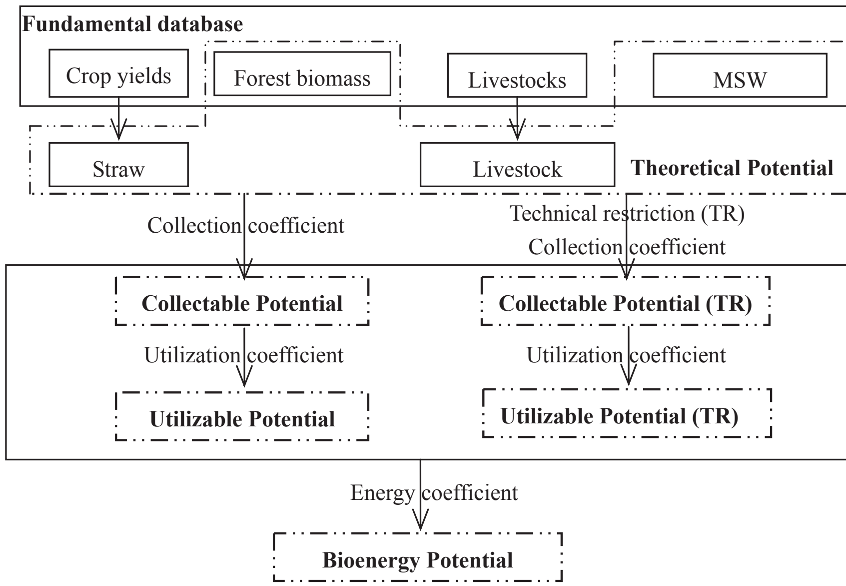

Fig. 1. Schematic diagram of biomass and ioenergy potential estimation.

countries. Under the pressure of food security, land degradation and a series of problems, the use of food is always in the center of argument. The main focus lays in the harmony between food security and energy security [9,10].

3. Biomass resources and their bioenergy potential estimation

Adequate raw material supply is the material basis for bioenergy industry development. Biomass resources estimation is done all around the world, so as to evaluate the possibility to promote bioenergy industry. For the time being, a common method to estimate bioenergy potential from biomass resources is as follow: subtract the amount of resources used in other ways and the loss during collection, transportation, etc. from the total amounts of every possible biomass types that could be used for bioenergy production. The rest amount is multiplied by energy conversion coefficient and converted to energy unit (Fig. 1). From the schematic diagram, the most important step is to determine the biomass amount that could be used as raw material of bioenergy production. According to the data source and method used in biomass resource amount estimation, there are two ways at present to estimate biomass and their energy potential. The first one is based on statistical data of every biomass types and in the other RS and GIS techniques are integrated Fig. 1.

3.1. Estimation based on statistical data

3.1.1. Methods

This is the most common used method in biomass and bioenergy potential estimation at present because of the ease in data acquisition. Estimation is done for specific biomass types.

(1) For agricultural residues and processing by-products, there is a formula provided by the Food and Agriculture Organization of the United Nations (FAO), which is the sum of the product of crop production (economic production) and residue product ration (RPR) of every crop type. RPR is the ratio of straw to grain for residues (straw and stalk), the ratio of by-product to crop consumption amount for by-products.
(2) It is similar to forestry residue and processing by-products. Taking technology development, collection and ecological environment conservation into consideration, woody biomass is defined as the woody resources could be used for energy or firewood and can calculated according to wood production or consumption amount and utilizable coefficient [11,12].
(3) The amount of waste biomass such as human excrement and urine, MSW and industrial waste water can be gathered from statistical yearbooks directly. The amount of animal excrement and urine is the product of the number of animals, excrement and urine amount per animal per time, breeding period, and collectable coefficient [13].
(4) Energy plants are introduced after the oil crisis in the latest 1970s, which are the plants specially cultivated for energy use not for food. Several countries are on the way of tests for their application, such as America, Sweden, Canada and Australia. The amount of energy plants is calculated according to their average production per area and the area planted. The production per area for several main energy plants are as follow: sugar cane (30 t/hm^2/yr), *Ophiopogon jaburan* (10 t/hm^2/yr), sorghum (15 t/hm^2/yr), versatile switch grass (9 t/hm^2/yr), eucalyptus (20 t/hm^2/yr), hybrid poplar (10–15 t/hm^2/yr), willow (8–10 t/hm^2/yr) [14–17].

Energy contained in biomass is a key factor affecting energy production from biomass and generally indicated by heat, which is the amount of heat generated in complete combustion under standard state. It is restricted by the components, element composition (especially carbon) in biomass. Higher and lower heating values (HHV and LHV) are both used when calculating energy potential in biomass. The two are different from each other in whether containing the heat from water vapor after burning or not. Waste biomass can be converted into energy not only through burning, but also through landfill to produce biogas. IPCC provides conversion formula for both MSW and waste water [18].

3.1.2. Biomass and their bioenergy potential estimated from statistical data

With the growth of concerns about bioenergy, studies about bioenergy potential estimation spring out all around the world. The difference in biomass resource selection and data source causes various results of bioenergy potential in different countries

and regions. In this part, we summarize existing research results in according to regionalization.

(1) The whole world
The gross bioenergy potential of the world changes from 64 to 161 EJ per year based on a “food first” estimation approach and a bioenergy scenario from FAO considering future agricultural development [19]. Total bioethanol production potential from crop residues and wasted crops is 491 GL[2] per year, in which 73.9 Tg[3] dry wasted crops in the world every year could produce 49.1 GL bioethanol, and about 1.5 Pg dry lignocellulosic biomass (442 GL bioethanol) [20]. Some researchers studied about the bioenergy potential of the world in 2050, but we could hardly find consistency among them, because of the difference in scenarios set and coefficients used in estimation. For example, Fischer and Schrattenholzer stated that bioenergy accounts for 15% of global primary energy by 2050 under a global energy scenario set by IIASA and the World Energy Council with high economic growth and low greenhouse gas emissions [21]. Based on a bottom-up model named QuickScan, the global bioenergy production in 2050 from agricultural and forestry residues and wastes is about 76–96 EJ[4] , and 74 EJ from surplus forest growth [5]. Thrän et al. found that bioenergy potential from energy crop changes from 27 EJ in 2010 to 96 EJ in 2050 in a “business as usual” scenario, and in “sustainable land use scenario” the two are 18 and 16 EJ, respectively [22].

(2) Europe
For the whole European region, bioenergy potential from dedicated bioenergy crops varies between 1.7 and 12.8 EJ/y, and the potentials for agricultural residues and forestry residues are 3.1–3.9 and 1.4–5.4 EJ/y, respectively [23]. Attainable bioenergy potential from rainfed production is about 60–120 GJ/ha for 1st generation and 100–180 GJ/ha for 2nd generation biofuel feedstocks [24]. De Wit et al. propose that with the development of agriculture, the extremes of European bioenergy potential, when considering average bioenergy crop yields, would probably go up to 5.1–9.3 EJ/year. And this number could be doubled by high yielding lignocellulosic crops [25]. In Mediterranean basin 13 Mtoe[5] ethanol could be produced from cereal crops, olive trees and tomato and grape processing waste in France, Italy, and Spain, Turkey and Egypt and 30 Mtoe from MSW [26]. Bioenergy from energy crops, agriculture and forestry residues and waste biomass could cover a total share of 7% in Switzerland [27]. Besides, much more researches about biomass and bioenergy potential in the countries in Europe are mentioned, such as Albania, Germany, Poland, and Spain [28–31].

(3) Asia
The biomass and bioenergy potentials from natural forest of Southeast Asia are 8.15×10^8 t and 16.3 EJ in 1990, and would be 3.59×10^8 t and 7.2 EJ in 2020 under sustainable development scenario [32]. In 2004 there are 7.28×10^8 t crop straw, 39.26×10^8 t excrement, 21.75×10^8 t woody biomass, 1.55×10^8 t MSW, and 482.4×10^8 t waste water in China. And these would provide total and theoretical bioenergy potential of about 35.11×10^8 and 4.6×10^8 tce [7,8]. In Japan urban waste can provide about 500–600 PJ energy potential, accounting for about 2–3% of the total energy consumption [33]. Taiwan would generate 36 to 56 Gg of methane per year during 1995–2007 using livestock manure [34]. If 10% of the 43.75 million ha marginal land in China was fully utilized for energy plants growth under a five species planting strategy, the production of bio-fuel would be 13.39 million tons [35]. Studies about biomass and bioenergy potential in other countries are also presented, such as Nepal, Malaysia Pakistan, Turkey and Thailand [36–39].

(4) America and Africa
4.0 million dry tons of woody biomass in Mississippi is available and 1.2 billion liters per year of ethanol could be produced [40]. The Pacific Northwest states of the USA has a potential of over 6.5 Mt of straw at current straw yields, about 2.4 Mg/ha [41]. In Argentina, biomass potential of switchgrass is about 99×10^6 (1.9 EJ) to 243×10^6 tdm (4.5 EJ) per year and soybean (crude vegetable oil content) production for bioenergy is about 7.1×10^6 (0.25 EJ) to 13.8×10^6 tdm (0.5 EJ) [42]. Fuelwood potential for semi-arid and arid sub-Saharan Africa under the current technical is about 4000 PJ per year [43]. Biomass contributes about 64% of the total primary energy supply in Ghana [44].

3.2. Estimation integrating RS and GIS techniques

The estimation and evaluation of biomass and bioenergy potential based on land surface survey and statistical data confronts with a series of problems affecting the efficiency and effectiveness, such as heavy work load, large scale, long update cycle and lack of spatial information. However, spatial information about biomass and bioenergy potential is essential to guide the intensive and efficient use of resource and the allocation of bioenergy related projects and industries. The development of remote sensing and GIS provides unlimited probabilities for spatial biomass and bioenergy potential estimation. As a new method introduced, the use of RS and GIS mainly presents in two aspects. The first one is to estimate biomass and net primary production (NPP) using RS and GIS so as to evaluate biomass resources. The other is to obtain area information about the land that could be used in biomass plantation. Unfortunately, RS and GIS are only useful for specific biomass types, because the theoretical basis is to measure vegetation biomass in ecological field. Thus, these techniques can be applied for the biomass types falling in both the ecology field and renewable energy field, that is to say, biomass originating from vegetations. Fig. 2 gives a quick view of the process of bioenergy potential estimation based on RS and GIS.

3.2.1. Bioenergy potential based on remotely-sensed biomass estimation

This method is suitable for bioenergy potential from agricultural and forestry residues and wastes based on biomass or NPP estimation. The flow of this method is to estimate total organic matter accumulation in agriculture and forestry at first. Then determine the available parts for bioenergy use based on decision-making model of bioenergy through influence factors analysis, which affects the availability of biomass for energy use. And the bioenergy potential is finally determined similar to the method used in statistical based estimations.

The foundation of this method is the remote sensing estimation model for biomass or NPP. Existing global and regional NPP datasets from MODIS were widely used improve the quality of a high resolution inventory of potentials of biomass energy, and provided a new way to simulate spatial distribution of biomass resources [45,46]. NPP estimated from Ecological models BIOME-BGC, light use efficiency model, and Agro-BGC etc. using multi-sensor remote

[2] GL, gigaliter, is a unit to measure volume of liquid equivalent to one cubic hectometer. 1 GL is equal to one billion liters.

[3] Tg, Pg are units for weight. 1 Pg $= 10^3$ Tg $= 10^{15}$ g.

[4] EJ is the unit for heat. 1 EJ $= 10^9$ GJ $= 10^{12}$ MJ $= 10^{15}$ KJ $= 10^{18}$ J.

[5] Mtoe is energy measured in standard coal equivalent. 1 Mtoe means the heat contained by 1×10^6 t standard coal.

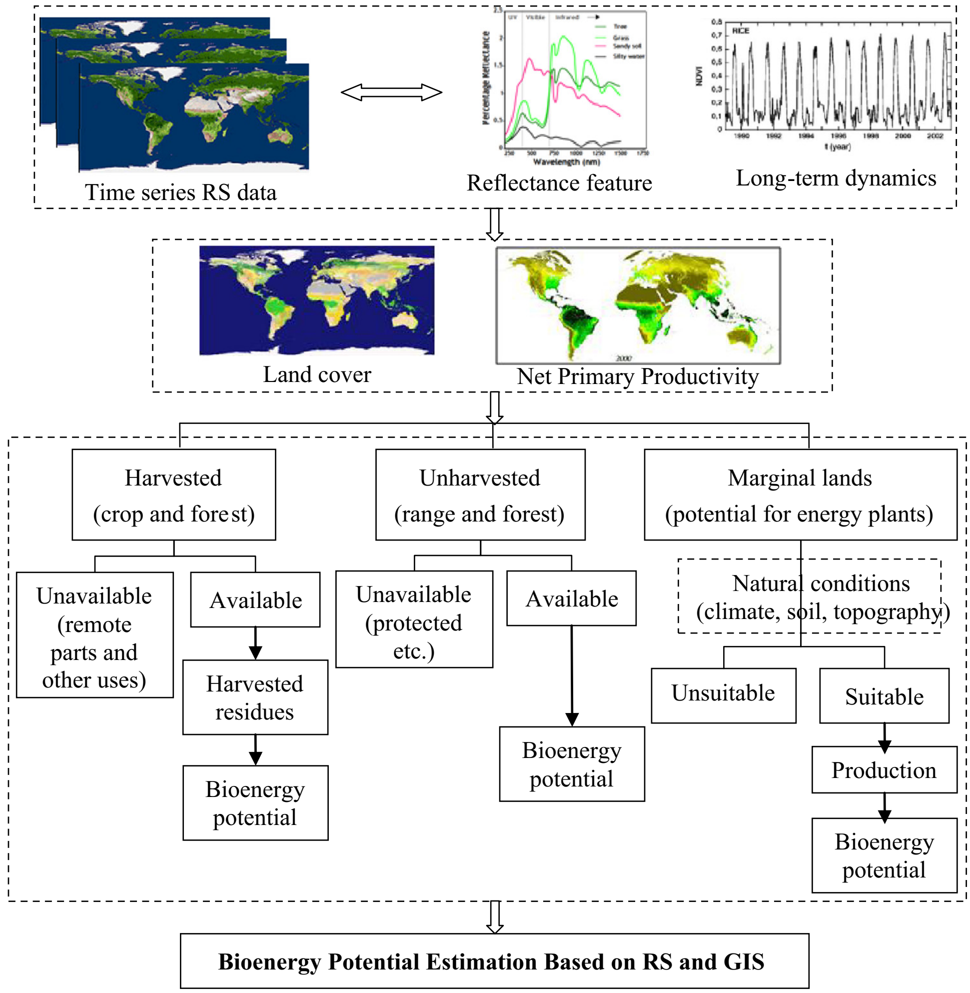

Fig. 2. Schematic diagram of bioenergy potential estimation based on RS and GIS.

sensing data were also considered for forest, grassland and agro-ecosystems [47–50]. Satellite derived biomass estimation was also used as raw materials [51]. Besides, RS data was also used as supplement to statistical and inventory data. For example, Baath et al. established an analysis and evaluation system for production status and potential evaluation of forestry bioenergy. The system has two main parts. The first one is forest ecosystem productivity estimation based on a combination between national forest inventory data and remote sensing data as TM and SPOT. The other is a forest planning and scenario model named Swedish Hugin system to forest fuels amount (from branches and tops) monitoring based on forecast and future harvesting levels setting [52].

RS and GIS techniques were often combined to reveal the availability of existing biomass resources for bioenergy use. To determine whether the existing biomass was accessible or collectable, information of protected areas, convenience of transportation, Road network could be extracted and the accessibility of biomass at a certain place could be analyzed based on multi-source data like economic, transportation, regional planning, digital elevation model and population datasets using RS and GIS techniques [53]. Pixel-based model integrating multi-coefficients about soil, topography, land use, water characteristics of vegetation growth and biomass accumulation was established to assess biomass accessibility [54–57]. The database and results above was also very useful to bioenergy trade-off management and to determine optimal location and capacity planning of distributed biomass power generation facilities [58–60].

3.2.2. *Land availability for bioenergy based on RS and GIS*

Land area occupied by every biomass resource is an indispensible indicator when estimating biomass resource amount from agriculture and forestry using existing method or according to production per area. Perhaps statistical yearbooks could be regarded as a source for it, but the disadvantages of statistical data become restraints for large-area and real time estimation. Using RS and GIS to determine land availability for bioenergy use is mostly for agricultural and forestry biomass and energy plants.

Unlike other biomass resources from agriculture and forestry, energy plants are specially cultivated for energy use. Bioenergy potential from energy plants are mostly determined by the cultivation conditions. Since energy plants have great competition with agriculture for land and have the potential to reduce soil fertility and to threaten food security, it is widely accepted that the development of energy plants should stand on the basis that energy plants do not replace existing forest or agriculture land and that land unused or with low utilize rate are the first priorities for energy plants cultivation [61] and its area is largely determined by natural condition and relative policies. Marginal land, including reserve land suitable for agriculture and forestry, marginal cropland, barren hills and slopes, as well as lands for firewood, oil wood and shrubs, is commonly recognized as proper land for energy plants cultivation [62]. Land use and cover map generated from remote sensing images can provide useful information lands occupied by different vegetation types and can help clarify potential land areas not only suitable for energy plants, but also

currently unused and satisfying the requirements of regional land use planning and relative ecological and environmental reservation conditions.

Marginal land could be characterized from classification of remote sensing images by selecting sub-types of land use dataset [63]. The meteorological, soil, topographic and so on could be applied to designate area suitable for the growth of a certain energy plant, according to its intrinsic biophysicochemical characteristics. The two areas were then overlapped to find out exact regions for energy crop planting [64,65]. The growth of the cultivated energy plant was simulated by vegetation growth models like 3PG to obtain biomass accumulation information [66,67]. It is reported that there were 3.85–4.72 $\times$ 10^8 ha surplus agricultural land that could be used for energy plants cultivation (4.3 t of aboveground biomass per ha per year)., bioenergy potential from energy plants cultivation in Europe is about 1.7–12.8 EJ/yr according to different development direction and rate [68].

4. Bioenergy potential estimation under different scenarios in the future

Biomass and bioenergy potential under different scenarios in the future could forecast the prospects of bioenergy development and its relative influence on environmental protection. There are different views about bioenergy supply potential in the future. Because of the complexity of influence factors affecting bioenergy potential, there is no conclusion for the debate yet. As we know, the factors influence bioenergy potential interact with each other and hardly be separated clearly [69]. So studies about bioenergy potential in the future are most likely to focus on one of the factors. The most widely discussed ones are bioenergy potentials according to climate change, economic and technical development and land use changes.

4.1. Climate change

Vegetation growth is one of the most important sources for bioenergy and it is seriously affected by natural and human environments changes influenced by climate change. Crop yield and energy plants cultivation under changing climate situation are direct influences for bioenergy potential. Bioenergy potential in the future under climate change scenarios are integrated with various types of climate models. Its temporal and spatial scales are often determined by the climate models. Climate change scenarios are often set according to the IPCC scenarios.

A typical research gave us insight into how to estimate bioenergy potential under climate change scenario was done by Tuck et al. [70]. Climate change scenarios were set according to the four IPCC SRES emission scenarios, AIFI, A2, B1 and B2, and they were implemented by four global climate models, HadCM3, CSIRO2, PCM and CGCM2, respectively. 26 promising bioenergy crops in 4 categories (oilseeds, starch crops, cereals and solid biofuel crops) suitable for temperate Mediterranean climate were studied and their potential distributions under different climate change scenarios were derived based on rules for suitable climate conditions and elevation. Results showed that because of increasing temperatures in northern Europe by the 2080s, the potential distribution of bioenergy crops was predicted to increase. However, it decreases in the southern Europe due to increased drought. The simulation of climate change scenarios were most likely to conduct in forest ecosystems due to their high influence and response to climate change [71,72].

4.2. Economic and technical development

During the development of human society, the economic and technical development, to some extent, determines the scope, extent and intensity of human activities, such as population, technical development level, intensity of land exploitation and land use, etc.. Beside the traditional use of biomass resources, the process of generating bioenergy from biomass is largely relying on economy and technology development. No matter in the near or far away future, bioenergy potential is fluctuating according to different economic and technical development speed and level. Bioenergy potential estimation under economic and technical development scenarios often starts from biomass resource availability affected by population, supply and demands, agriculture and forestry development, technical development, land use changes, which varies according to different economic and technical development speeds and levels.

The most important step of bioenergy potential estimation under economic and technical development was scenarios definition. Economic growth speed, population growth speed and per capital consumption level, and technical development levels were the most important economic and technical factors. They were often divided into different levels. Various combinations of the factors in different levels affected the demands of food, wood and ecological environment conservation, resource availability for bioenergy and the energy conversion efficiency. The bottom-up QuickScan model gave a convenience framework for bioenergy potential estimation in these situations. Results showed that bioenergy potentials from surplus agricultural land, agricultural residues and wastes, and forestry residues in 2050 are 215–1272 EJ/yr, 76–79 EJ/yr and 74 EJ/yr, respectively [5].

4.3. Land use change

In order to response to climate change and energy crisis, a series of polices and measures are proposed to promote the development of bioenergy. The market and price temptations for bioenergy development would lead to considerable conversion of traditional ways of biomass use and would bring out significant influence to agriculture and forestry production. The limitation of land suitable and available for biomass production inevitably arouses competition for land among agriculture, forestry and bioenergy development. This is the origination of the conflict between bioenergy development and agriculture production and food security [73]. Global bioenergy potential in 2050 vary from 100 to 400 EJ/yr due to the difference in land area available for bioenergy and crop yield [74].

Land use change and simulation models are introduced to the process of bioenergy potential estimation, so as to evaluate the influence of land use change on bioenergy potential comprehensively and systematically [12]. Multi-regional global-land-use-and-energy model (GLUE-11) expanded from a two-region GLUE model was extended to evaluate the global bioenergy potential from energy plants, residues and wastes in the future. This model considered competition in land use and covers a wide range of biomass flow such as food chains, paper recycling, and biomass residues production [75]. Regional and global cost-supply curves and different land use scenarios of abandoned agricultural land, low-productivity land and rest land was also used to reveal bioenergy potential in 2050 (130–270 EJ/yr with a production cost of 2 dollars/GJ) [76]. Lotze-Campen et al. integrated spatial land use pattern with agricultural productivity and combined economic land use allocation model and process-based vegetation–hydrology model to simulate bioenergy potential under various scenarios with different technical levels, land use pattern and global trade-off [31].

The three categories above about bioenergy potential in the future are the most common ones for the time being. As the variety of influence factors for bioenergy potential, there are researches from other aspects as well, such as scenarios with different crop yield and feed conversion efficiency and sustainable development scenario. Overall, estimation of bioenergy potential in the future is a considerable complicated system, involving integrating influence from natural, social, economic and technical aspects. Standing at the start line of bioenergy industry development, it is essential to forecast and foresee the desired future of bioenergy. Thus, bioenergy potential in the future is an area worthy for further study.

5. Questions and the future

Future bioenergy potential researches are conducted in both the global and regional scales with simplified estimation models. Although we have taken a great step, there are still some weakness and undeveloped areas remaining to deal with. The status and shortage of existing bioenergy potential estimation are:

(1) Not all the resource types are in discussion
There are considerable amount of biomass resources that could be used as energy. However, in bioenergy potential estimation, biomass types involved are almost limited, agricultural and forestry residues and energy plants. Animal excrement, MSW and waste water are slightly involved, but rare to see. As the foundation of bioenergy industry development, it is necessary to have raw material information as complete as possible. Woody biomass has the greatest biomass and bioenergy potential and has best development potential in the future with the progress of economy and technology. At present, hampered by technical feasibility, woody biomass fails to attract enough attention. In bioenergy potential estimation, processing by-products and residues are most commonly concerned. More attention should be paid to utilizable but unused forestry biomass like secondary forest and firewood.

(2) Lack of spatial attributes
Data source used in bioenergy potential estimation are mainly statistical data, absent of spatial attributes. Information about total amount only is not adequate for the industrialization of bioenergy. Spatial distribution of bioenergy potential would guide several steps on the industry chain more effectively and efficiently, such as the collection of raw material, the allocation of primary production factories and projects, the cost-benefits analysis, etc.. For the further progress of bioenergy industry, spatialized database about biomass and bioenergy potential, not only in global, regional and national scale, but also in county scale or even smaller spatial scales, will play a great role in the future of bioenergy.

(3) Researches about energy plants starts preliminarily
As an important increase point for bioenergy resource, the research of energy plants almost lies in the aspects of experiment and demonstration. However, there is no doubt that energy plants are the most important raw material for bioenergy industry in the long run. How to explore energy plants cultivation under the situation of food security and ecological environment health is in pressing need for deeper study. Marginal land, the most potential land resource for energy plants cultivation, is another hot issue in bioenergy researches. Besides the area and productivity potential of marginal land in bioenergy development, the eco-environmental effects of marginal land exploration should inevitably be added into the agenda of energy plants development.

(4) Studies of bioenergy potential under different scenarios in the future are systematically formed
Researches about bioenergy potential under different scenarios in the future are carried out step by step. As a systematic and complicated system, it is hard to do thorough analysis of bioenergy potential in the future. But it is indispensable to guide the development and future of bioenergy. Thus, from the perspective of human macro-control, bioenergy potential controlled by human under scenarios in line with the development of human society would provide favorable basis for bioenergy industry development.

In the future, bioenergy potential estimation should focus on the following aspects. From the perspective of the origination of biomass resources, special attention should be paid to woody biomass due to its huge biomass potential, as well as its conversion and utilization techniques. Similar to the bioenergy use of MSW and wastes from animal husbandry to generate methane, garbage in rural areas cannot be ignored, not only because of its large potential, but also because of the its potential harm to ecological environment. This is particularly important in developing countries, where perfect garbage recycling and utilization system has not been established perfectly. From the perspective of estimation approaches, RS, GIS and such methods with spatial characteristics should be introduced. Traditional estimation gives statistical information in administrative division unit. Detailed spatial attributes of bioenergy potential should be taken in the first place into consideration. This can help a lot to collect biomass, locate and plan distributed bioenergy power generation facilities, trade off of bioenergy products and so on. From the perspective of effective use of biomass, quality evaluation of biomass and bioenergy is particularly essential.

The estimation of biomass and bioenergy potential is significant and complicated project. It is also the first step that human recognize and understand the appearance and future of bioenergy industry. In order to strongly guide the development of bioenergy industry in raw material supply level, the estimation of bioenergy potential is, to some extent, a feasibility analysis process to evaluate bioenergy industry. It also provides basic data support for rational exploration and intensive use of bioenergy. Therefore, researches about bioenergy potential estimation are absolutely necessary and waiting for further exploration.

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